

VERY HIGH REPETITION RATE POWER SUPPLY SYSTEM AND METHOD

TO WHOM IT MAY CONCERN:

BE IT KNOWN THAT George L. Bees of 12 Woodstock Drive, Framingham, Middlesex County, Massachusetts, 01701, invented certain new and useful improvements entitled as set forth above of which the following is a specification:

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3 VERY HIGH REPETITION RATE POWER SUPPLY SYSTEM AND METHOD

4
5 BACKGROUND OF THE INVENTION

6 (1) Field of the Invention

7 The present invention relates generally to power supply
8 systems, and more particularly to power supply systems for high
9 repetition rate pulse discharge driven systems.

10 (2) Description of the Prior Art

11 A large ampere current pulse that is a requirement of pulse
12 discharge driven systems, is often realized through a capacitor
13 that is charged to a certain voltage and discharged at a
14 specified time to deliver the energy required of the pulse
15 discharge driven system. Examples of pulse discharge driven
16 systems include Doppler radar and lasers. In these systems, it
17 is necessary to deliver the energy from the capacitor to the
18 system in a precise manner, wherein the precision relates to the
19 timing of energy delivered, and the amount of energy delivered.
20 For instance, in a Doppler radar system, it is necessary to
21 deliver the same energy each pulse repetition interval to allow
22 the return signals to be properly processed, as fluctuations in
23 the delivered energy may cause variability in the transmitted
24 pulses that are then misinterpreted by the receiver. Similarly,
25 a laser system requires the same precision in timing and energy

1 for proper laser operation, as there is a nonlinear relationship
2 between the energy delivered and the laser performance.

3 Prior art power supply systems utilize peaking capacitors in
4 magnetic pulse compression circuits to provide a repetitive, high
5 voltage, high energy charge to a peaking capacitor in a short
6 duration. In such systems, multistage LC networks typically
7 convert long, relatively low voltage pulses into the desired
8 short, high voltage pulses. Other prior art systems include
9 pulse power supply systems that supply excimer lasers with high
10 voltage, short pulses. The majority of the prior art systems,
11 however, operate in the 1000 Hz range. One prior art system
12 operating at higher frequencies does not allow asynchronous
13 operation, as the power supply system operation is coordinated
14 precisely with the pulse discharge driven system. In that prior
15 art system, the timing between the pulse discharge driven system
16 and the charging capacitor reaching a specified voltage, must be
17 synchronized precisely, as the problem of maintaining a specified
18 voltage across a capacitor is well-known.

19 There is not currently an asynchronous power supply system
20 for pulse discharge driven systems, wherein the power supply
21 system may operate at higher repetition frequencies and not
22 require synchronous coordination with the pulse discharge system.

23 What is needed is an efficient power supply system to
24 accurately operate at higher pulse rates, wherein the power

1 supply system may operate asynchronously with respect to the
2 pulse discharge driven system.

3

4 SUMMARY OF THE INVENTION

5 It is an aspect of the invention to provide a power supply
6 system that supplies electrical pulses to a pulse discharge
7 driven system. In one aspect of the invention, the power supply
8 system includes a pulse generating circuit with a charging
9 inductor and a charging capacitor, wherein the charging capacitor
10 drives the pulse discharge driven system. It is another aspect
11 of the invention to select the charging inductor to achieve a
12 time constant that is coordinated with the pulse rate of the
13 pulse discharge driven system.

14 In one embodiment, the pulse generating circuit further
15 includes a "keep up" high-voltage power supply, three solid-state
16 switches, and a diode. The voltage across the capacitor is
17 initially charged through the main power supply, wherein the time
18 to charge the capacitor is determined in part by the charging
19 inductor value. The capacitor voltage is monitored and compared
20 to a predetermined "control" voltage that is less than a
21 "driving" capacitor voltage that satisfies the requirements of
22 the pulse charge driven system. Upon the capacitor voltage
23 attaining the control voltage, a control module commands a solid-
24 state switch to disconnect the main power supply from the
25 circuit, thereby resulting in a sourceless (R)LC circuit that

1 allows the capacitor to continue charging at a more controlled
2 rate through the inductor discharge. Once the capacitor charges
3 to the driving voltage, the control module commands two solid-
4 state switches to separate the inductor from the capacitor, and
5 similarly, the control module commands the keep-up supply to
6 monitor and maintain the capacitor charge. If the capacitor
7 discharges before the pulse discharge system utilizes the
8 capacitor charge, the keep-up power supply replenishes the
9 capacitor charge to the driving voltage.

10 It is another aspect of the invention that when the
11 capacitor is discharged by the pulse discharge system, the
12 control module returns the pulse generating circuit to its
13 original state, incorporating the main power supply and inductor
14 by returning the solid-state switches to their original states.

15 It is another aspect of the invention to supply power to a
16 pulse discharge driven system, wherein the pulse discharge driven
17 system is a laser.

18 Other objects and advantages of the invention will become
19 obvious hereinafter in the specification and drawings.

20

21 BRIEF DESCRIPTION OF THE DRAWINGS

22 A more complete understanding of the invention and many of
23 the attendant advantages thereto will be readily appreciated as
24 the same becomes better understood by reference to the following
25 detailed description when considered in conjunction with the

1 accompanying drawings, wherein like reference numerals refer to
2 like parts and wherein:

3 FIG. 1 displays a power supply system that incorporates the
4 principles of the invention;

5 FIG. 2 displays the power supply system circuit of FIG. 1
6 while the power supply system is charging a capacitor from the
7 main power supply;

8 FIG. 3 presents the power supply system circuit of FIG. 1
9 wherein the capacitor is charging from an inductor;

10 FIGs. 4a and 4b present the power supply system circuits
11 derived from the power supply system of FIG. 1, wherein the keep-
12 up supply is maintaining the capacitor charge; and,

13 FIG. 5 illustrates the capacitor charging cycle throughout
14 the power supply system circuits of FIGs. 2-4B.

DESCRIPTION OF ILLUSTRATED EMBODIMENTS

To provide an overall understanding of the invention, certain illustrative embodiments will now be described; however, it will be understood by one of ordinary skill in the art that the systems described herein can be adapted and modified to provide systems for other suitable applications and that other additions and modifications can be made to the invention without departing from the scope hereof.

Referring now to FIG. 1, there is shown a power supply system 10 that incorporates the principles of the invention. As illustrated in FIG. 1, the power supply system 10 charges a capacitor 12 that is coupled through a switch 14 to a pulse discharge driven system 16. Those skilled in the art will recognize that the capacitor 12 is merely illustrative and may be represented by any other well known component with capacitive properties. Similarly, examples of pulse discharge driven systems include lasers and Doppler radars, for example, although this invention is not limited to a specific pulse discharge driven system. For the purposes of this discussion, the pulse discharge driven system 16 will be referred to as a laser. The switch labeled S4 14 and otherwise referred to herein as S4, may be any switching device or circuitry that applies the capacitor voltage to the laser 16, and may include solid state switches, for example. In the FIG. 1 illustration, an S4 control system may control S4 14, wherein such control system is not depicted in

1 FIG. 1. The S4 control system may operate S4 14 according to
2 laser pulsing requirements. For example, if the laser operates
3 at a frequency of 2000 Hz, the S4 control system may cause S4 14
4 to close every 500 microseconds for a predetermined length of
5 time.

6 The power supply system 10 as illustrated charges the
7 capacitor 12 to ensure that the capacitor voltage is the value
8 required to drive the laser 16, hereinafter referred to as the
9 driving voltage. The capacitor value is therefore dictated by
10 the laser 16 specifications. Because pulse driven systems such
11 as lasers have operational characteristics that are nonlinear
12 with respect to the driving voltage, it is a necessary
13 requirement that the driving voltage be accurately determined and
14 delivered. As FIG. 1 illustrates, the driving voltage for the
15 laser 16 is provided by the capacitor 12, and the difficulties of
16 maintaining a constant and precise charge across a capacitor are
17 well known in the art. The FIG. 1 power supply system 10,
18 however, discloses a system wherein resonant circuitry is
19 incorporated to maintain a specified driving voltage across the
20 capacitor 12.

21 The various elements of the power supply system 10 are
22 illustrated in FIG. 1, and are described relative to FIG. 1
23 briefly, with the detailed operation and interconnections to be
24 further detailed and understood by the descriptions of FIGs. 2,
25 3, and 4. As FIG. 1 indicates, the power supply system 10

1 includes a main power supply 18. In an embodiment, the main
2 power supply 18 is a 20 KW phase shifted zero voltage switch
3 pulse width modulated (PWM) converter, operating at approximately
4 40 KHz, that converts three-phase line power to 1200 VDC,
5 although such power supply specifications are merely illustrative
6 and the invention herein is not limited to any specific main
7 power supply. The illustrated system 10 also includes three
8 switches labeled S1 20, S2 22, and S3 24, all of which may be any
9 switching device, but in an embodiment, all of which are solid
10 state switches. The invention does not require that the switches
11 be of same or similar type to each other.

12 The illustrated charging inductor 26 is selected to provide
13 a time constant that allows a capacitor charge time that
14 satisfies, i.e., is less than, the pulse rate of the laser 16.
15 For the illustrated system, for example, the charge time is
16 approximately equal to $\pi * \sqrt{L*C}$. Two resistors, R1 28 and R2 30,
17 are connected in parallel with the capacitor 12 in a commonly
18 known voltage divider configuration. A keep-up power supply 32
19 is also connected in parallel with the capacitor 12, and in an
20 embodiment, the keep-up power supply 32 is a high voltage power
21 supply, although the invention is not limited by the keep-up
22 power supply 32 specifications, and any similarly functioning
23 element as described herein, may therefore be substituted without
24 departing from the invention. The power supply system 10 also
25 includes a control module 34 that operates S1 20, S2 22, S3 24,

1 and controls the operation of the keep-up power supply 32, and
2 the main power supply 18. The illustrated control module 34 is
3 not microprocessor based however those skilled in the will
4 recognize that the control processor may be a microprocessor
5 based device, including for example, a personal computer (PC),
6 SUN workstation, laptop or handheld computer including personal
7 digital assistant (PDA), connected through a network or in a
8 stand-alone capacity, and functioning as described herein,
9 without departing from the scope of the invention. As FIG. 1
10 indicates, the control module 34 and the keep-up power supply 32
C11 measure the voltage drop across R1 28. The remaining element of
C12 the power supply system 10 is a diode 36.

13 Referring now to FIG. 2, there is illustrated a simplified
14 power supply system circuit 40 that is representative of the FIG.
15 1 power supply system 10 wherein switches S1 20 and S2 22 are
16 closed, and switch S3 24 is open. Recall from FIG. 1 that the S1
17 20, S2 22, and S3 24 switch operation is controlled by the
18 control module 34. The FIG. 2 illustration is representative of
19 the initial charge configuration, and shall be referred to herein
20 accordingly.

21 From FIG. 2, one with ordinary skill in the art will
22 recognize that the main supply 18 charges the capacitor 12 and
23 inductor 26. The control module 34 immediately and continually
24 monitors the voltage across R1 28 to maintain an accurate
25 measurement of the voltage across the charging capacitor 12.

1 Once the control module 34 determines that the capacitor 12 is
2 charged to a predetermined percentage of the specified driving
3 voltage, the control module 34 commands S1 20 to open, thereby
4 disconnecting the main power supply 18 from the remainder of the
5 power supply system 10. The predetermined percentage may be a
6 function of the driving voltage, the keep-up supply 32
7 characteristics, and the laser (pulse discharge driven system) 16
8 characteristics.

9 Referring now to FIG. 3, there is shown the simplified
10 circuit of FIG. 1 wherein S1 20 is open, S2 22 is closed, and S3
11 is open. In an embodiment, this switch configuration,
12 represented by the FIG. 3 circuit, is commanded by the control
13 module 34 when the control module 34 measures that the capacitor
14 12 is charged to 95% of the driving voltage. As FIG. 3
15 indicates, the main power supply of FIGS. 1 and 2 is no longer
16 connected to the circuit power supply system segment that
17 includes the capacitor 12. One with ordinary skill in the art
18 will recognize that the sourceless circuit of FIG. 3 will cause
19 the inductor 26 to discharge with an exponential decay, with
20 current flowing through the diode 36, and allowing the capacitor
21 12 to continue charging at a slower rate than the charge rate
22 provided by the main power supply 18 in FIG. 2. The control
23 module 34 continues to monitor the capacitor 12 through R1 28,
24 and when the control module senses that the capacitor 12 has
25 charged to 100% of the specified driving voltage, the control

1 system 34 commands S2 22 to open, and S3 24 to close.
2 Additionally, the control module 34 activates the keep-up supply
3 32 to monitor and maintain the capacitor 12 charge.

4 FIGs. 4A and 4B represent the simplified circuit diagram of
5 FIG. 1 wherein switch S1 20 is open, S2 22 is open, and S3 24 is
6 closed. As FIGs. 4A and 4B illustrate, the FIG. 1 power supply
7 system 10 simplifies into two individual circuits for the given
8 switch configuration. The circuit illustrated by FIG. 4A
9 includes the main power supply 18, the inductor 26, and the
10 diode 36. Any energy remaining in the inductor 26 will be
11 transferred to the main power supply 18.

12 Alternately, the circuit illustrated in FIG. 4B includes the
13 series combination of R1 28 and R2 30, connected in parallel with
14 the capacitor 12, and similarly in parallel to the activated
15 keep-up supply 32. Those skilled in the art will recognize that
16 if the capacitor 12 is not discharged by the laser 16 of FIG. 1
17 nearly immediately after the switch configuration represented by
18 FIGs. 4A and 4B is achieved, the voltage across the FIG. 4B
19 capacitor 12 will exponentially decay through R1 28 and R2 30,
20 and other system losses; therefore, the activated keep-up supply
21 32 monitors the loss through R1 28 and compensates for the loss
22 by recharging the capacitor 12. In an embodiment, the
23 illustrated keep-up supply 32 activates whenever the keep-up
24 supply 32 determines the capacitor discharge loss exceeds one
25 volt. The keep-up supply 32 continues to replenish the capacitor

1 12 to maintain the capacitor voltage at the desired driving
2 voltage. This replenishing cycle performed by the keep-up supply
3 32 may continue indefinitely. In this configuration, the control
4 module 34 also continues to monitor the voltage across the
5 capacitor 12 by measuring the voltage drop across R1 28.

6 Those skilled in the art will recognize that the keep-up
7 supply 32 monitoring and maintenance functions may be performed
8 in many ways while remaining within the scope of the invention.
9 For example, the keep-up supply 32 may receive and store the
10 driving voltage, and compare the measured voltages to the stored
11 driving voltage to determine when the capacitor 12 requires
12 recharging. The keep-up supply 32 may measure the voltage
13 across R1 28 using well-known sample-and-hold technology, using
14 either digital or analog circuitry, but the invention is not
15 limited to such technique. Alternately, the control module 34
16 may provide the driving voltage to the keep-up supply 32, or the
17 keep-up supply driving voltage reference may be established as
18 that voltage first measured by the keep-up supply 32 after the
19 control module 34 activates the keep-up supply 32.

20 Those skilled in the art will also recognize that the
21 control module 34 may measure the capacitor voltage using many
22 different well-known techniques, some of which are referred to in
23 the discussion of the keep-up supply 32, without departing from
24 the scope of the invention. Because the illustrated control
25 module 34 continuously monitors the voltage across the capacitor

1 12, the control module 34 measures the significant capacitor
2 voltage drop that occurs when, in the present example, the
3 capacitor 12 is discharged by the illustrated laser 16 of FIG. 1.

4 The illustrated laser 16 of FIG. 1 presents an output load
5 with extremely small impedance; therefore, when switch S4 14
6 closes, the capacitor voltage is discharged to the laser 16, but
7 the load mismatch between the capacitor 12 and the laser 16
8 causes a reversal of current, and hence a reversal in the sign of
9 the voltage at the capacitor 12. Referring now to FIG. 5, there
10 is shown the voltage across the capacitor 12 as a function of
11 time 50. As FIG. 5 indicates, the capacitor voltage is at the
12 driving voltage 52 when S4 is closed 54, whereupon within, for
13 example, approximately five to ten microseconds in some
14 applications, the capacitor 12 discharges, wherein the capacitor
15 voltage drops from the driving voltage 52, to a negative voltage
16 56. Those skilled in the art will recognize that this negative
17 voltage represents energy that may be expressed by the well known
18 expression of $\frac{1}{2}CV^2$, where C is the capacitor 12 value, and V is
19 the voltage across the capacitor.

20 Upon the control module 34 sensing the significant and
21 nearly instantaneous capacitor voltage drop that occurs when S4
22 14 is closed, the control module 34 returns the power supply
23 system 10 to the initial charge configuration of FIG. 2, wherein
24 S1 20 is closed, S2 22 is closed, and S3 24 is open.
25 Additionally, the control module 34 deactivates the keep-up

1 supply 32. The power supply system 10 is therefore returned to
2 the initial charge configuration of FIG. 2. In this
3 configuration, however, the inductor 26 is connected to the main
4 power supply 18 on one end, and the capacitor 12 with negative
5 voltage at the other end. This difference in voltage, in
6 combination with the diode 36 preventing current flow away from
7 the inductor 26, causes a large current surge through the
8 inductor that transfers the energy in the capacitor 12 to the
9 inductor 26 and facilitates a more responsive charge of the
10 inductor and capacitor to meet the laser 16 requirements. This
11 inherent recovery of capacitor 12 energy due to the capacitor
12 voltage reversal facilitates a power supply system 10 that is
13 compatible with higher repetition rate laser.

14 In alternate embodiments, the control module 34 may sense
15 the discharge by the pulse discharge driven system 16 by
16 receiving a signal from the pulse discharge driven system 16, for
17 example. Those skilled in the art will recognize that other
18 methods of sensing the capacitor discharge may be incorporated
19 without departing from the invention.

20 In another embodiment, the control module 34 may control the
21 main power supply 18 for shut-down in the case of system failure.

22 This series of charging the capacitor 12, in this example,
23 to 95% of the driving voltage, as shown by FIG. 2, thereafter
24 removing the main power supply 18 to allow the inductor 26 to
25 continue charging the capacitor 12 to 100% of the driving

1 voltage, as illustrated and demonstrated by FIG. 3, and
2 activating the keep-up supply 32 to maintain the capacitor charge
3 as shown by FIG. 4B, continuously repeats with the required
4 frequency and duration specified by the pulse discharge driven
5 system 16, wherein the cyclic capacitor voltage may be
6 illustrated by FIG. 5. As shown by FIG. 5, although the
7 illustrated power supply system 10 components are selected to
8 satisfy a pulsing interval 58 of the laser 16, it is not
9 necessary that the power supply system 10 be synchronized
10 precisely with the laser pulsing interval 58. For example, prior
11 art power supply systems that cannot indefinitely maintain the
12 charge across the driving capacitor 12, are coordinated precisely
13 with the end of each pulsing interval 58 to ensure the fully
14 charged capacitor condition occurs synchronously with the laser
15 discharge.

16 One of several advantages of the present invention over the
17 prior art is that the power supply system 10 may charge and
18 thereafter maintain a charge across the capacitor 12 to drive the
19 pulse discharge driven system 16, wherein the capacitor charging
20 and maintenance thereof is not required to be synchronized with
21 the discharge by the pulse discharge driven system 16.

22 What has thus been described is a system and method for a
23 power supply system that charges a capacitor, wherein the
24 capacitor charge drives a pulse discharge driven system. The
25 power supply system utilizes a main power supply and a resonant

1 inductor and capacitor configuration to charge the capacitor to a
2 specified, large percentage of a driving voltage that is required
3 by the pulse system. A control module monitors the capacitor
4 charge and disconnects the main power supply when the capacitor
5 charge is within the specified percentage. The main power supply
6 disconnect causes the inductor to discharge and similarly charge
7 the capacitor in a more controlled manner. Once the control
8 module measures the capacitor voltage at the full driving
9 voltage, the control module commands a switch to separate the
10 inductor from the capacitor. The control module similarly
11 activates a small high voltage power supply that monitors the
12 capacitor and replenishes any natural capacitor discharge that
13 may occur in the time between the full capacitor charge and the
14 capacitor discharge by the pulse discharge driven system. Once
15 the pulse discharge driven system discharges the capacitor, the
16 control module returns the power supply system to its initial
17 state, wherein the main power supply and residual energy in the
18 capacitor cooperate to efficiently charge the inductor and
19 capacitor. The charging cycle continues repeatedly as a function
20 of the pulse discharge driven system requirements.

21 Although the present invention has been described relative
22 to a specific embodiment thereof, it is not so limited.
23 Obviously many modifications and variations of the present
24 invention may become apparent in light of the above teachings.
25 For example, the system presented herein represented a laser, but

1 other pulse discharge driven systems may be substituted.

2 Although the example charged the capacitor to 95% of the driving
3 voltage before separating and deactivating the main power supply,
4 such criteria is merely for illustrative purposes and other
5 values may be selected. The switches in an embodiment are solid
6 state devices, however any other switching mechanism may be used.

7 Similarly, all switches are not required to utilize the same
8 technology. The main power supply represented may be any power
9 supply supplying any waveform or signal sufficient to charge the
10 inductor and capacitor to the desired values. Similarly, the
11 keep-up supply may be substituted by any device or mechanism that
12 may perform the functions described herein and attributed to the
13 keep-up supply in measuring and maintaining the capacitor
14 voltage. The control module includes any device capable of
15 monitoring and controlling the switches and power supplies as
16 described herein. Similarly, functions such as those described
17 for the keep-up supply and control module, for example, may be
18 combined into a single device without departing from the scope of
19 the invention. The control module may sense that the capacitor
20 was discharged by the pulse discharge driven system by measuring
21 the voltage, or alternately, by monitoring the switch to the
22 pulse discharge driven system, or obtaining a signal from a pulse
23 discharge driven system control module, indicating that the
24 capacitor was discharged. The voltage divider configuration may
25 be eliminated and substituted with another scheme.

Many additional changes in the details, materials, steps and arrangement of parts, herein described and illustrated to explain the nature of the invention, may be made by those skilled in the art within the principle and scope of the invention.

Accordingly, it will be understood that the invention is not to be limited to the embodiments disclosed herein, may be practiced otherwise than specifically described, and is to be understood from the following claims, that are to be interpreted as broadly as allowed under the law.

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